D/H MEASUREMENTS

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Primordial evaluations of the deuterium abundance should provide one of the best tests of Big Bang nucleosynthesis models. Space as well as ground based observations seem however to result in different values. This asks for more observations in different astrophysical sites in order to link present day interstellar medium D/H evaluations to primordial ones. New investigations, made with FUSE (the *Far Ultraviolet Spectroscopic Explorer* launched in June 1999), are presented and in the case of the white dwarf G191-B2B line of sight a low D/H evaluation of $1.16 \pm 0.24 \times 10^{-5}$ (2σ) is confirmed. This seems to indicate that D/H variations are probably present in the nearby interstellar medium. The FUSE observations should help us reach in a near future a better global view of the evolution of that key element.

1 Introduction

During primordial Big Bang nucleosynthesis deuterium is produced in significant amounts and then destroyed in stellar interiors. It is thus a key element in cosmology and in galactic chemical evolution (see *e.g.* Audouze & Tinsley [1]; Boesgaard & Steigman [2]; Olive *et al.* [3]; Pagel *et al.* [4]; Vangioni-Flam & Cassé [5, 6]; Prantzos [7]; Scully *et al.* [8]; Cassé & Vangioni-Flam [9]).

The *Copernicus* space observatory has provided the first direct measurement of the D/H ratio in the interstellar medium (ISM) representative of the present epoch (Rogerson & York [10]) :

$$(\mathrm{D/H})_{\mathrm{ISM}}^{Copernicus} \simeq 1.4 \pm 0.2 \times 10^{-5}.$$

More recently D/H evaluations were made in the direction of quasars (QSOs) in low metallicity media. They were completed toward three different QSOs' (Burles & Tytler [11, 12]; O'Meara & Tytler [13]) leading to a possible range of $2.4 - 4.8 \times 10^{-5}$ for the primordial D/H. These values correspond to a new estimations of the baryon density of the Universe, $\Omega_{\mathrm{b}}\mathrm{h}^2 = 0.019 \pm 0.0009$, in the frame of the standard BBN model (Burles *et al.* [14]; Nollett & Burles [15]). When compared to the recent $\Omega_{\mathrm{b}}\mathrm{h}^2$ evaluation made from the Cosmic Microwave Background (CMB) observations (see *e.g.* Jaffe *et al.* [28]) $\Omega_{\mathrm{b}}\mathrm{h}^2 = 0.032 \pm 0.005$, this seems to lead to a possible conflict. Note that another D/H measurement made toward a low redshift QSO leading to a D/H value possibly larger than 10^{-4} (Webb *et al.* [17]; Tytler *et al.* [18]) corresponds to an even stronger disagreement since it translates into $\Omega_b h^2 \leq 0.01$.

It is thus important to investigate the possibility of varying D/H ratios in different astrophysical sites (see *e.g.* Lemoine *et al.* [19]). If variations are indeed found, their cause should be investigated before a reliable primordial D/H evaluation can be inferred from a small number of observations.

2 Interstellar observations

Several methods have been used to measure the interstellar D/H ratio. All will not be discussed here and for more details see *e.g.* Ferlet [20]. The more reliable approach is to observe in absorption, against the background continuum of stars, the atomic Lyman series of D and H in the far-UV.

Toward hot stars, with the *Copernicus* satellite, many important evaluations of D/H were obtained (see e.g. Rogerson and York [10]; York and Rogerson [21]; Vidal–Madjar *et al.* [22]; Laurent *et al.* [23]; Ferlet *et al.* [24]; York [25]; Allen *et al.* [26]) leading to the detection of variations recently enforced by HST–GHRS (Vidal–Madjar *et al.* [27]) toward G191–B2B showing a low value and IMAPS observations, one made toward δ Ori presenting again a low value (Jenkins *et al.* [28]) confirming the previous analysis made by Laurent *et al.* [23] from *Copernicus* observations and the other one toward γ^2 Vel with a high value (Sonneborn *et al.* [29]). These observations seem to indicate that in the ISM, within few hundred parsecs, D/H may vary by more than a factor $\simeq 3$.

From published values, D/H ranges from

$$\sim 5 \times 10^{-6} < (\mathrm{D/H})_{ISM} < \sim 4 \times 10^{-5}.$$

This method also provided a precise D/H evaluation in the local ISM (LISM) in the direction of the cool star Capella (Linsky *et al.* [30]) :

$$(\mathrm{D/H})^{\mathrm{GHRS}}_{\mathrm{Capella}} = 1.60 \pm 0.09^{+0.05}_{-0.10} \times 10^{-5}$$

Additional observations made in the LISM lead Linsky [31] (see references there in) to the conclusion that the D/H value within the Local Interstellar Cloud (LIC) is (compatible with 12 evaluations) :

$$(\mathrm{D/H})^{\mathrm{GHRS}}_{\mathrm{LIC}} = 1.50 \pm 0.10 \times 10^{-5}$$

3 The nearby ISM

Observations of white dwarfs (WD) in the nearby ISM (NISM) for precise D/H evaluations were first proposed and achieved in the direction of G191–B2B by Lemoine *et al.* [32] using the HST–GHRS spectrograph at medium resolution. Follow up observations on G191–B2B at higher resolution with the GHRS Echelle-A grating by Vidal–Madjar *et al.* [27] (same instrument configuration used as in the Capella study) lead to a precise D/H evaluation in the NISM

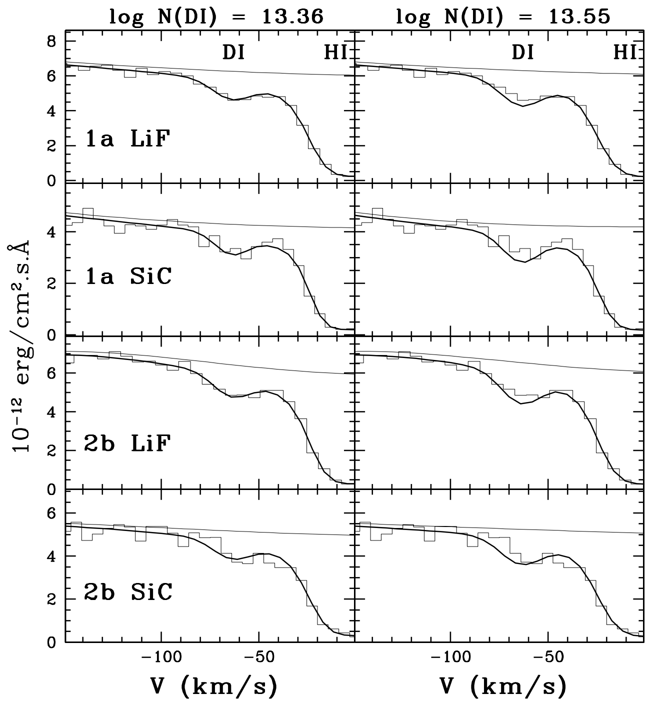

Figure 1. FUSE observations made in the direction of G191–B2B. The Lyman β line is shown in the four FUSE channels recorded simultaneously through the high resolution slit (two LiF and two SiC). On the left panels the fits are shown with the best FUSE evaluation made by Vidal–Madjar *et al.* [35] and on the right ones with the D column density evaluated by Sahu *et al.* [33] with the STIS instrumentation which is more than 6σ incompatible with the FUSE observations.

along this line of sight within one HI region – the Local Interstellar Cloud (LIC) also observed toward Capella (these stars are separated by $\sim 7^o$ on the sky) – and within a more complex and ionized HII region presenting a double velocity structure. In these two main interstellar components the D/H ratio was found to be different if one assumes that the D/H value within the LIC is the same as the one found in the direction of Capella, in which case D/H has to be lower ($\sim 0.9 \times 10^{-5}$) in the more ionized components.

In any case a lower "average" D/H ratio is found (2σ error) :

$$(\mathrm{D/H})^{\mathrm{GHRS}}_{\mathrm{G191-B2B}} = 1.12 \pm 0.16 \times 10^{-5}$$

This result has been contested by Sahu *et al.* [33] who used new HST–STIS high resolution Echelle observations. However Vidal–Madjar [34] has showed that all data sets (GHRS and STIS) in fact converge on a same value of the D/H ratio, which furthermore agrees with that derived by Vidal–Madjar *et al.* [27] and disagrees with that of Sahu *et al.* [33].

Since the disagreement between the two analysis was on the DI column density estimation, FUSE observations were expected to clarify the situation since they give access to weaker deuterium Lyman lines that are less sensitive to saturation effects than Lyman α. Three independent data sets were obtained corresponding to the three different FUSE entrance apertures (Vidal–Madjar *et al.* [35]). The fits of the D Lyman β line in the various FUSE channels are shown in Figure 1 and compared with the estimate of Sahu *et al.* [33]. These new data confirm the measurement of N(DI) of Vidal–Madjar *et al.* [27]; the value N(DI) derived by Sahu *et al.* [33] lies 6σ away from the new result. These 6σ are quantified in terms of $\Delta\chi^2$, including many possible systematics such as stellar continuum placement, zero level, spectral instrument shifts, line spread function profiles, all free in the fitting process (see e.g. the different stellar continuum levels in Figure 1 from left to right panels).

The HI column density toward G191–B2B is well determined. Independent measurements with EUVE (Dupuis *et al.* [36]), GHRS (medium[32] and high resolution[34]) and STIS (high resolution[33]) using several methods of evaluation (EUV, Lyman continuum opacity and Lyman α, damping wing modelling), converge on a value of log N(HI) = 18.34 ($\pm$0.03). The error on this value includes systematic errors associated with the various measurement techniques.

Using the DI column density as measured by FUSE and the HI column density compatible with all published values, one arrives at (2σ error) :

$$(\mathrm{D/H})^{\mathrm{FUSE-HST-EUVE}}_{\mathrm{G191-B2B}} = 1.16 \pm 0.24 \times 10^{-5}$$

This value is marginally compatible ($\geq 2\sigma$) with the LIC one.

The essential question remains : if D/H variations are confirmed in more sightlines, what could be their cause ?

4 The FUSE observatory

FUSE starts to produce orders of magnitude more data on the distribution of D/H in the ISM. From the planned D/H survey, we should be able to evaluate the deuterium abundance in a wide variety of locations, possibly linked to the past star formation rate as well as to the supposed infall of less processed gas in our Galaxy, and thus better understand Galactic chemical evolution.

The FUSE sensitivity should allow evaluations of the deuterium abundance in tens of lines of sights : i) in the direction of white dwarfs and cool

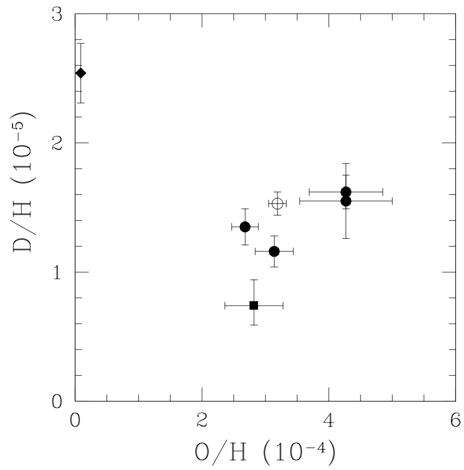

Figure 2. Different D/H evaluations as a function of O/H (1σ errors). The diamond is the observation made in the direction of a QSO by O'Meara and Tytler [13] corresponding to a low metallicity cloud; the square is the IMAPS observation in the direction of δOri by Jenkins *et al.* [28] in the ISM; the filled circles correspond to the FUSE observations (and among them the G191–B2B one) and the open circle to the average of 12 lines of sight through the LIC observed by GHRS and STIS from Linsky [31] in relation to the ISM O/H evaluation made by Meyer *et al.* [43] from their survey.

stars in the NISM ; ii) toward hot sub-dwarfs in the more distant ISM and nearby Galactic halo ; iii) within the Galactic disk over several kilo-parsecs in the direction of O and early B stars ; iv) in the more distant Galactic halo, within high velocity cloud complexes as well as in intergalactic clouds in the direction of low redshift QSOs, AGNs and blue compact galaxies.

The first precise D/H evaluations toward few white dwarfs were presented in early 2001 at the AAS meeting (Moos *et al.* [37]; Friedman *et al.* [38]; Hébrard *et al.* [39]; Kruk *et al.* [40]; Linsky *et al.* [41]; Sonneborn *et al.* [42]; Vidal–Madjar *et al.* [35]). The deuterium Lyman lines are clearly seen toward these few WDs and, as an example, the Lyman β line is shown in the case of G191–B2B as previously discussed (see Figure 1). Several of these D/H evaluations made in the ISM with FUSE, HST, IMAPS are shown in Figure 2 along with one made recently in the direction of one QSO from ground based observations [13], as a function of the line of sight average metallicity as traced by O/H when available. It seems that the D/H variation does not anti–correlate with O/H. Thus a simple mechanism as astration, able to destroy D and produce O, does not seem compatible with the observations. Other mechanisms should be investigated as the ones listed by *e.g.* Lemoine *et al.* [19].

5 Conclusion

In summary the status of the different – but discordant – D/H evaluations taken with no a priori bias to select one over another could be the following.

If the variations of the D/H ratio in the NISM are illusory, one could quote an average value of $(\mathrm{D/H})_{\mathrm{NISM}} \simeq 1.3 - 1.4 \times 10^{-5}$ barely compatible with all observations.

More in agreement with the present observations, D/H seems to vary in the ISM. One has thus to understand why.

Until then, any single or small number of values should not be considered to represent the definitive D/H in a given region. This is particularly true for the "primordial" values found in the direction of QSOs since the physical state of the probed environment is more poorly known than the Galactic one.

Our hope is that the FUSE mission will solve these problems.

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